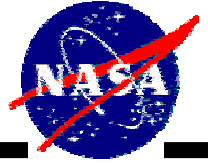# HRTF Results

Les Deutsch
**Jet Propulsion Laboratory**

August 16, 2001

HRTF Results
Background

- The Huygens probe carried by Cassini is to be released to Titan from orbit about Saturn

- Huygens will descend into Titan's atmosphere as Cassini flies overhead

- Images, physical measurements, and radio science will be gathered during the descent into the atmosphere, expected to take about 150 minutes

- If Huygens survives on the surface, science will be performed until Cassini reaches Titan

- Cassini/Huygens is a joint ESA/NASA mission

- ESA built the Huygens spacecraft and both ends of the relay radio for the one-way telemetry link

- This link was tested on the ground before launch – but the kinds of signal dynamics expected in the real mission could not be realistically reproduced

- It was discovered in a DSN/Cassini test in February, 2000 that the link fails under worst case dynamic conditions of the expected mission

esa
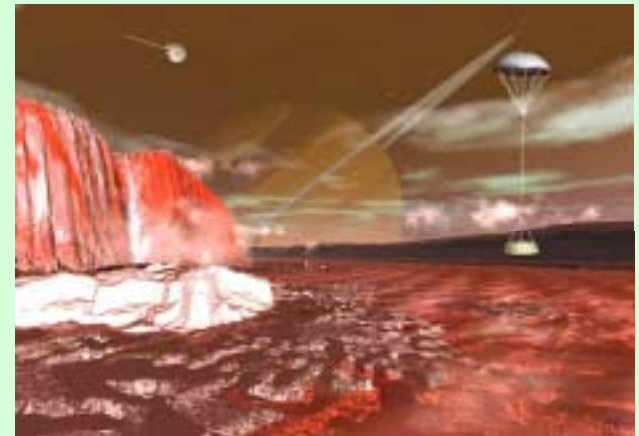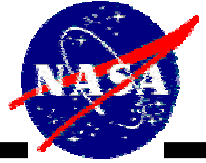
The Huygens Recovery Task Force shall:

- **Analyze in depth the Huygens failure mode and effect and verify it by simulations, ground and in-orbit tests;**

- **Evaluate scenarios to recover the mission in close cooperation with the NASA/JPL Cassini Program Office. These scenarios shall consider (but are not restricted to):**

  - **Reduce the sensitivity of Huygens to the Doppler effect by changing the RF link characteristics and/or by modifying the on-board and on-ground data handling**

  - **Analyze how to reduce the Doppler effect and the effects this might induce on the Cassini/Huygens mission profile**

- **Evaluate and verify the effectiveness of above scenarios and quantify its technical and programatic impact on the Huygens and Cassini baseline missions.**

The Huygens Recovery Task Force shall perform its task within a period of six months starting 1 January 2001. It shall report on a monthly basis to J. Credland, ESA/ESTEC and E. Huckins, NASA HQ, and give a final presentation of its results together with recommendations for implementation to the ESA Director of Science and NASA Associate Administrator for Space Science.

eesa
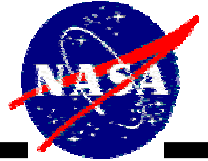
1 Jan 01

Failure Investigation

Testing FM/EM
Analyses
Modeling, verification

Recovery Design

Sensitivity analysis
Parameter verification
Δf: flyby altitude/velocity
      oscillator manipulation
E_S/N_0: ODT/antenna pointing
P_t: data manipulation
      zero packets
Corrupted data recovery

Options
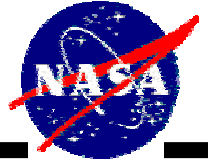
30 Jun 01

Gain/impact assessment
Design of options

Decision
ESA/NASA
Directors

HRTF Results
Status

- The HRTF completed its technical work in June

- A final presentation was made at the Cassini Project Science Group (PSG) meeting in Oxford on June 19, 2001

- The recommendations were accepted in a joint NASA/ESA resolution drafted by Earle Huckins and John Credland

- The PSG executive body resolved to advocate the recommendations and work with the NASA and ESA projects during implementation

- The HRTF final report has been completed and is downloadable from an ESOC server

- The HRTF has ended and implementation teams are being assembled to do the real work
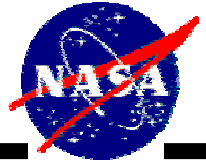
- **The HRTF is a truly international multifunctional team with representatives from JPL, ESTEC, ESOC, Alcatel, Alenia, and GMV**

- **JPL provided major support to this effort**

- **Much of the work shown here is the result of the following JPL people:**

HRTF Members

- **Leslie J. Deutsch (HRTF co-chair)**
- **Earl H. Maize**
- **Jeremy B. Jones**
- **Kenneth S. Andrews**
- **Nathan J. Strange**

Cassini Project Participants
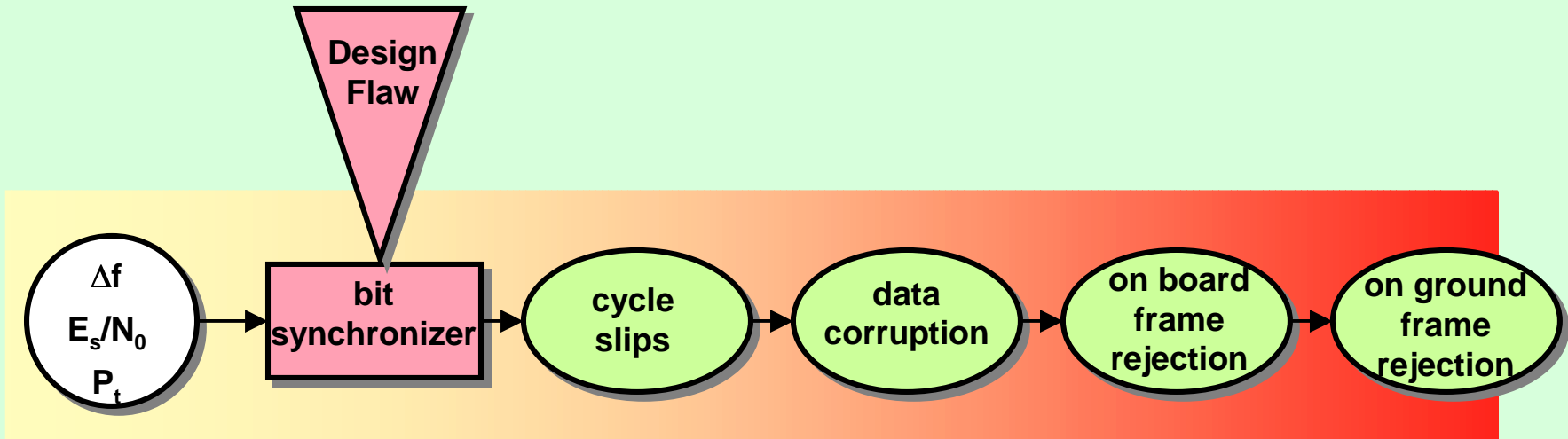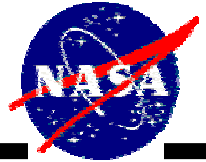
- **Robert T. Mitchell**
- **Dennis L. Matson**

HRTF Support Experts

- **Dariush Divsalar**
- **Jon Hamkins**
- **Norman E. Lay**
- **Fabrizio Pollara**
- **Yungsun Hahn**
- **Fernando Peralta**
- **Troy Goodson**
- **Duane Roth**
- **Aron Wolf**
- **Richard Horttor**
- **Anthony Lee**
- **Michael Sierchio**
- **Julie Webster**
- **Guy Kauffman (AlliedSignal)**

- **Earle Huckins (NASA Code S) was an active member of the team, proving that we can work together with HQ under the right circumstances!**
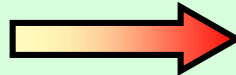
esa

Design Flaw

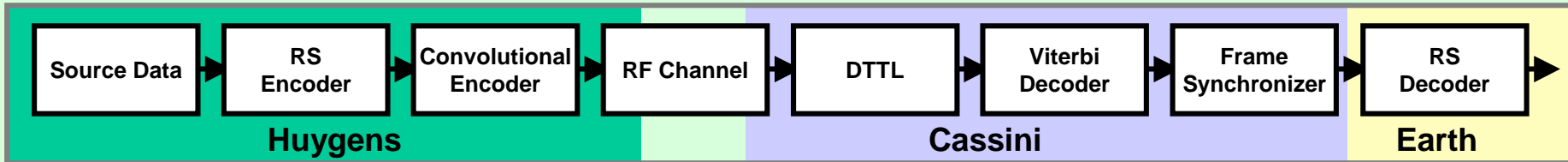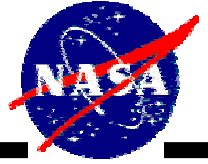| Δf E_s/N_0 P_t | → | bit synchronizer | → | cycle slips | → | data corruption | → | on board frame rejection | → | on ground frame rejection |

Relevant Parameters   **The Problem**   **The Effect** →

- **Because of a design flaw, the bit synchronizer in the Probe Support Avionics (PSA) of Cassini slips cycles under certain combinations of Doppler, signal-to-noise ratio, and bit transition density in the data stream**

- **This results in poor PSA frame synchronization resulting in**
  - **Some corrupted frames sent to Earth**
  - **Some frames discarded in the PSA completely ("dump frames")**

- **Current ground equipment cannot recover many of the corrupted frames**

esa

Source Data	RS Encoder	Convolutional Encoder	RF Channel	DTTL	Viterbi Decoder	Frame Synchronizer	RS Decoder

**Huygens** **Cassini** **Earth**

- The Huygens communication system is distributed between the probe, the Cassini orbiter, and the Earth

- Only one piece, the Data Transition Tracking Loop (DTTL) is known to be anomalous

- The DTTL anomaly results (under certain conditions) in data symbol slips

- These symbol slips cause errors in the bit stream as delivered to Earth, but in a very complex way

- We can observe the behavior of the various Probe Support Avionics (PSA) subsystems by examining the PSA's housekeeping telemetry stream
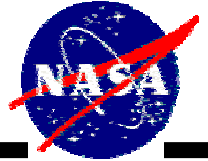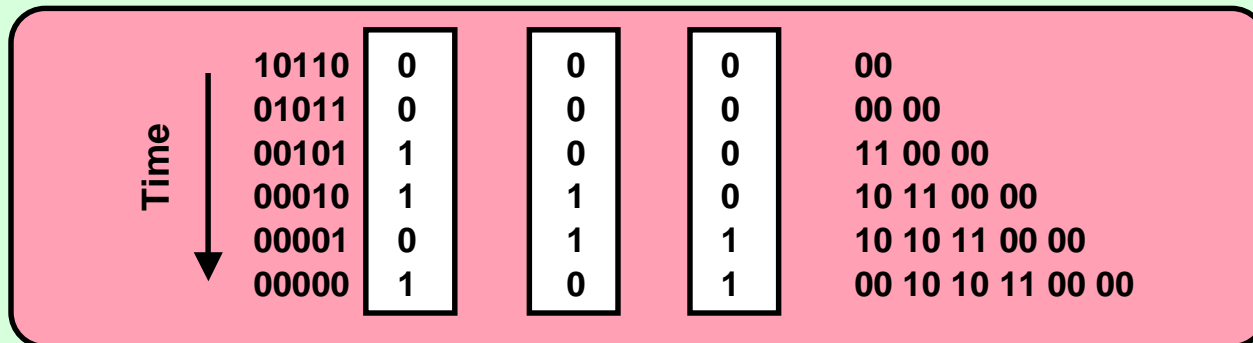
Convolutional Codes **create redundancy in an iterative fashion rather than in predefined codeword sizes as in block codes**
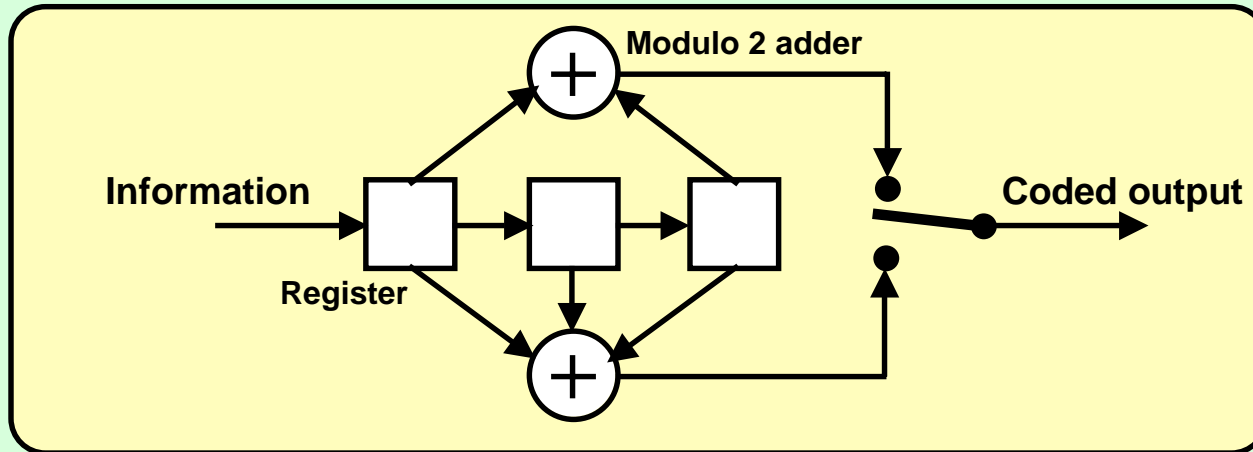
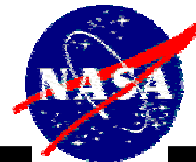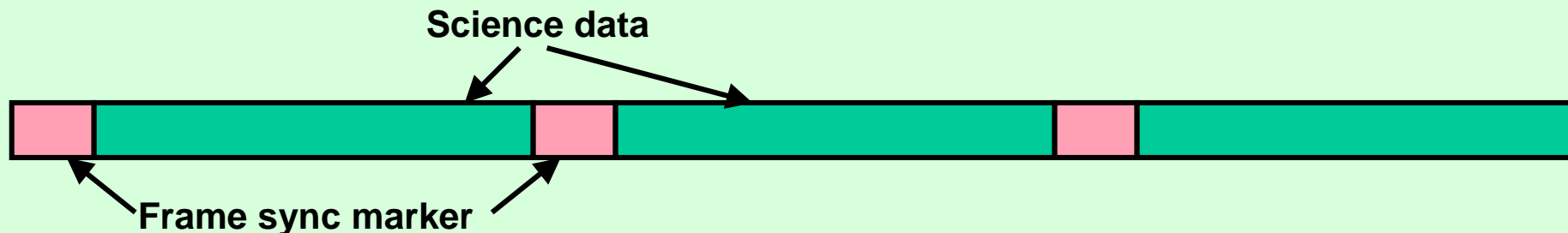**How it works:**

In order to undo this, the decoder (Viterbi decoder) must know which bit in the pair is the first – "node synchronization"

- A known pseudorandom sequence of bits is inserted at the beginning of each frame of data
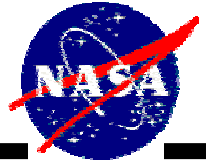
Science data

Frame sync marker

- The frame synchronizer looks for this sequence in the data stream to acquire synchronization
- As long as it keeps seeing the sequence in the expected places, synchronization is maintained (tracking mode)
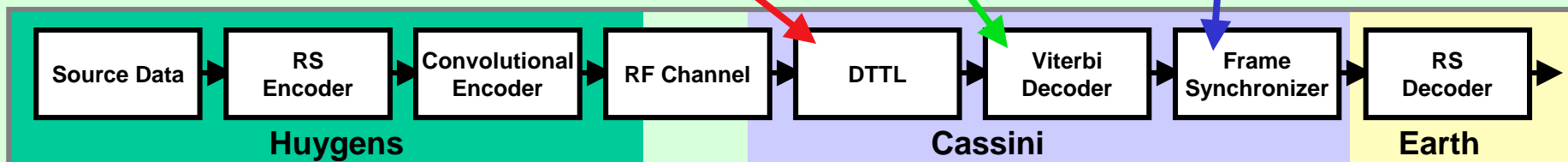- If the sync marker fails to appear for a certain number of expected locations, loss of sync is declared

- **PSA subsystem performance can be monitored by examining the information returned in the PSA housekeeping packets**

Time	Carr Lock	SC Lock	FFT Res.	Bit Sync.	Viterbi Dec.	Sync. Stat.	AGC	Rec Freq	RSW
	R50019.raw	R5001C.raw	R5001B.raw	R5001D.raw	R5001A.raw	R5002C.raw	XA8001.syn	XA8000.syn	R5003A
2001.035.03.03.46.731	1	1	1	8	8	8	512	-893.3188	6
2001.035.03.03.46.856	1	1	1	8	8	8	507	-892.496	6
2001.035.03.03.46.981	1	1	1	8	8	8	517	-891.4796	6
2001.035.03.03.47.106	1	1	1	8	8	8	522	-890.1244	6
2001.035.03.03.47.231	1	1	1	8	8	8	522	-892.98	6
2001.035.03.03.47.356	1	1	1	8	8	8	525	-892.98	6
2001.035.03.03.47.481	1	1	1	8	8	8	523	-891.6248	6
2001.035.03.03.47.606	1	1	1	8	8	8	515	-895.642	6
2001.035.03.03.47.731	1	1	1	8	8	8	518	-899.1752	6
2001.035.03.03.47.856	1	1	1	8	8	8	515	-898.8364	6
2001.035.03.03.47.981	1	1	1	8	8	8	509	-905.1768	6
2001.035.03.03.48.106	1	1	1	8	8	8	510	-909.3392	6
2001.035.03.03.48.231	1	1	1	8	8	8	511	-905.1768	6
2001.035.03.03.48.356	1	1					505		6
2001.035.03.03.48.481	1	1							
2001.035.03.03.48.606									

Indicates the DTTL is in trouble

Indicates the Frame synchronizer is in trouble

Indicates the Viterbi decoder is in trouble

| Source Data | → | RS Encoder | → | Convolutional Encoder | → | RF Channel | → | DTTL | → | Viterbi Decoder | → | Frame Synchronizer | → | RS Decoder | → |

Huygens   **Cassini**   **Earth**

HRTF Results
Long Dwell Tests
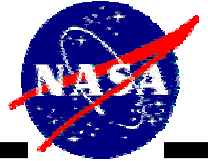
- **All testing in PRT#1 and with the EM was accomplished keeping the three relevant parameters constant for about 60 frames**

  - **Frequency offset**

  - **Bit transition probability**

  - **Signal to noise ratio**

- **This was not enough time to observe patterns of errors in the received data**

- **For PRT#2, a number of long dwell test points were planned**

- **These points were chosen with combinations of parameters that would cause errors**

- **Each of these points was several hundred frames in length**

Huygens Probe OFF

Cassini
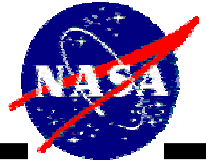
High Gain Antenna

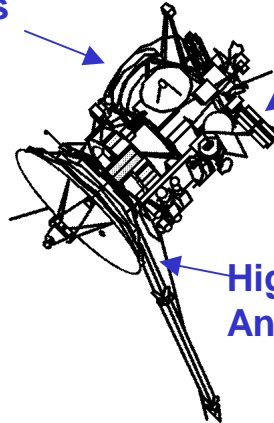**S-band (2 GHz) radio signal transmission from Goldstone simulating Huygens Probe transmission (one-way light time is 40 min)**

X-band (8 GHz) Cassini telemetry
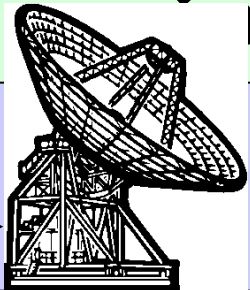
Huygens Test Equipment

JPL

ESOC

DSS 24 Deep Space Network Antenna

Data Evaluation

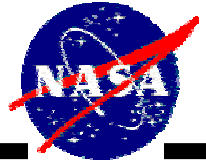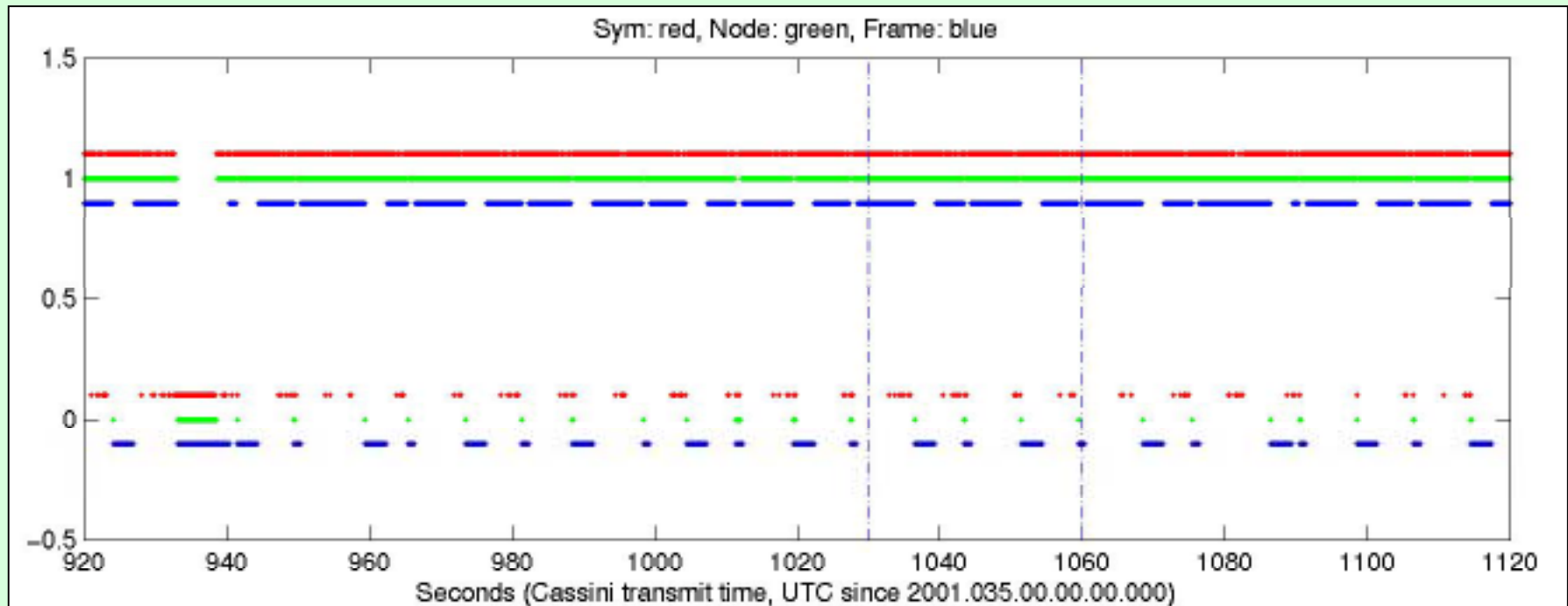**Data arrive at ESOC 80 min after transmission From Goldstone!**

DSS 24

Boris Smeds and Test Equipment

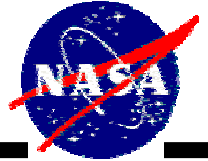LJD-13
07/10/01

HRTF Results
What We Saw

- **Here is a piece of the long dwell sequence results**
- **In the graph below, the "bit sync," "node sync," and "frame sync" signals from the housekeeping data are plotted, with a small offset so we can look at them all at the same time**


Sym: red, Node: green, Frame: blue

Seconds (Cassini transmit time, UTC since 2001.035.00.00.00.000)

HRTF Results
Zoom In And Look

- **Problems occur after DTTL losses, as expected**
- **There are patterns of alternating "1" and "3" frame problems**
- **Each frame sync "event" coincides with a short node sync "event"**
  - **The node sync event is always aligned perfectly with the start of a frame**
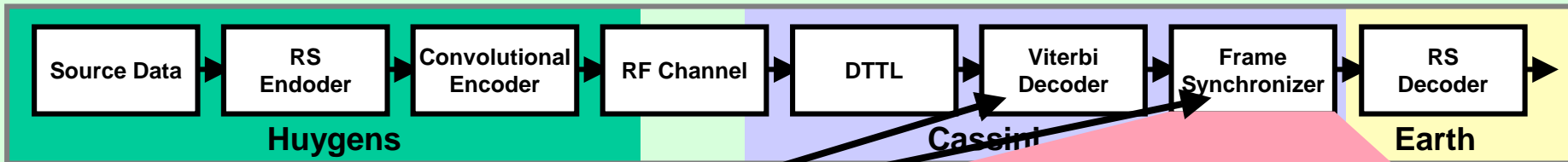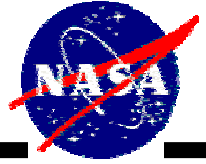
**DTTL Events before
loss of frame sync**
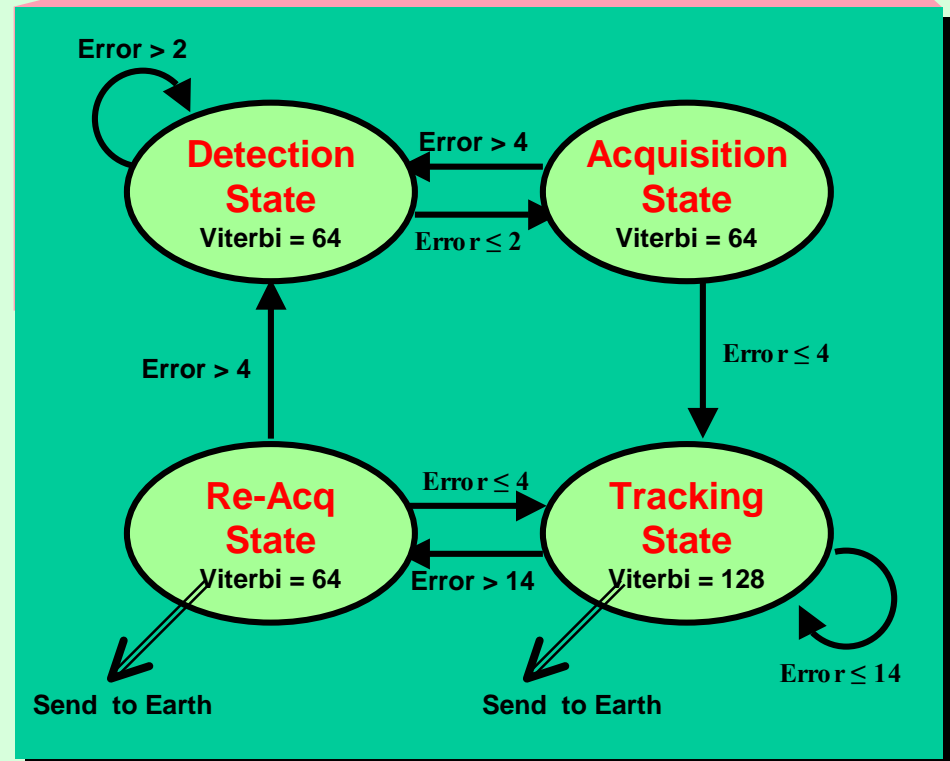
**Node sync event at
start of frames**
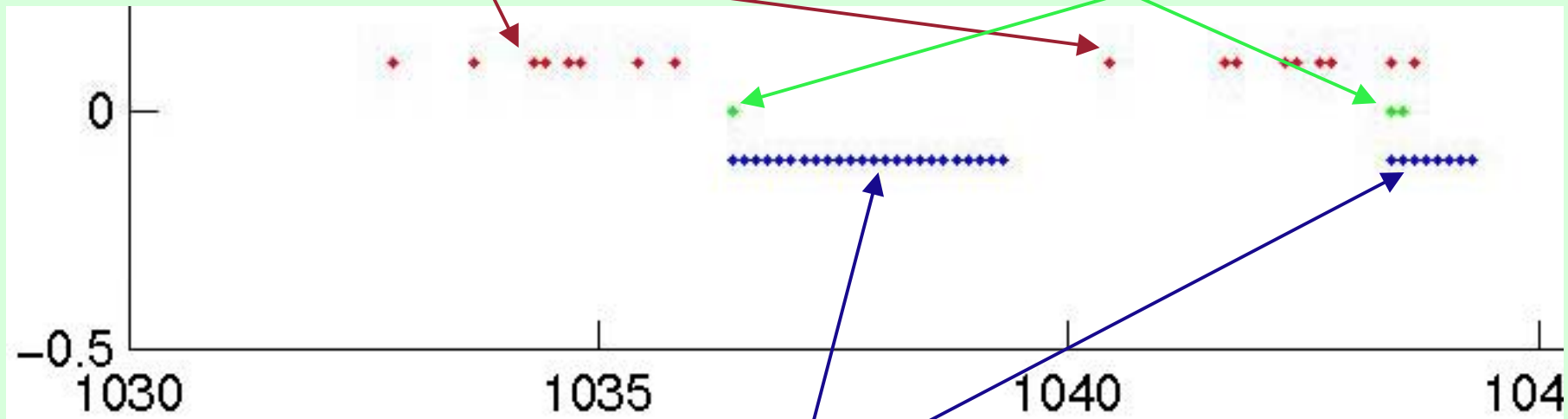
**Alternating frame events
of length 1 and 3**

- **The patterns we saw could be explained by considering the interaction of the frame synchronization algorithm with the Viterbi decoder**

- **Notice that the frame synchronizer changes the Viterbi decoder node sync threshold in the "tracking state"**

- **This is the key to the corruption model**

HRTF Results
## The Corruption Model – First Part
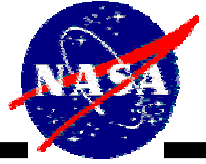
- We assume we are starting in the "tracking state" with everything in sync

- The DTTL slips a symbol

- The Viterbi decoder, being set to too small a threshold, fails to detect that it has lost node sync and continues decoding, putting out bad data

- The next time a frame sync marker should come, there is bad Viterbi decoded data instead

- The frame synchronizer moves to the "re-acquisition state." It also sets the Viterbi threshold to 64

- Now that the Viterbi decoder has a different threshold, it immediately detects (correctly) that it has lost sync

- The Viterbi decoder quickly regains node sync

- In regaining node sync, the Viterbi decoder has slipped a single symbol, not a whole bit, so the next frame sync marker is still in the right place

- The frame sync marker is detected in the right place and we move back to the "tracking state." The housekeeping data records a single frame outage
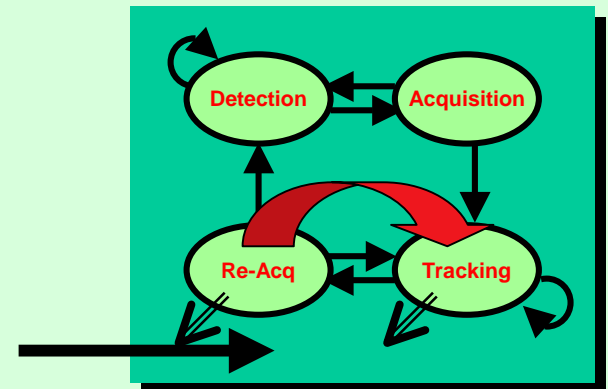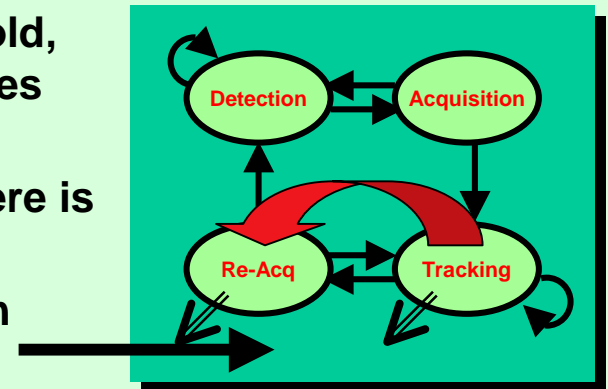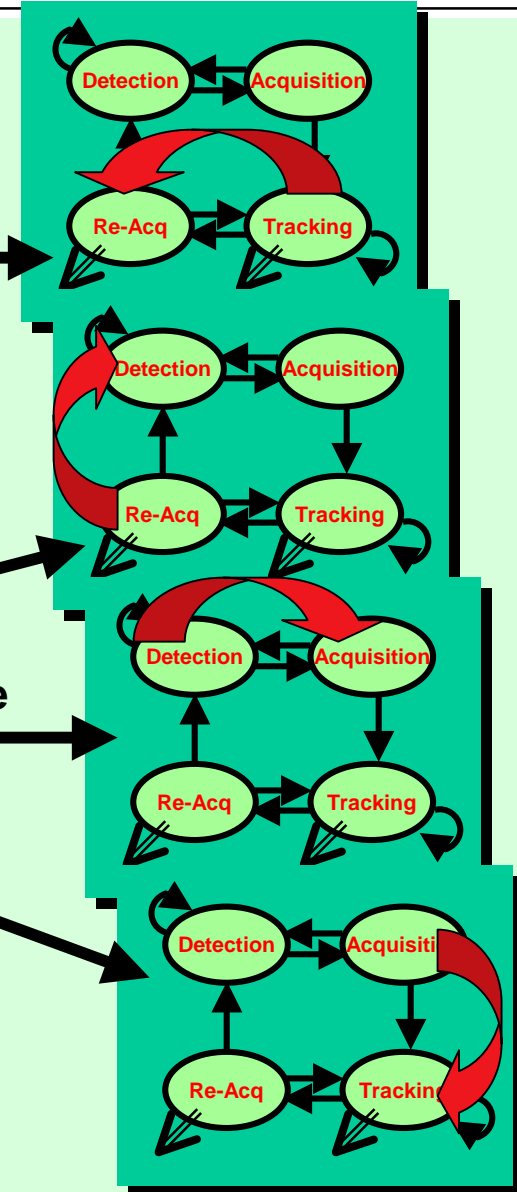
HRTF Results
## The New Corruption Model – Second Part
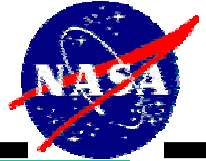
- **Again, we get a DTTL event, the Viterbi decoder puts out bad data, since it once again has the higher threshold**
- **Once again, we fail to detect a frame sync marker and go to the "re-acquisition state"**
- **Once again, the Viterbi decoder notices immediately that it has lost sync and regains it quickly**
- **Now, however, we have slipped a second symbol and the Decoder ends up slipping an entire bit!**
- **Because of the bit slip, and the fact that we are in re-acq state, the frame synchronizer fails to find the next marker and goes into the "detection state"**
- **It takes one more frame to find the marker and move to the "acquisition state"**
- **It takes yet another frame to get back to the "tracking state"**
- **Meanwhile, the housekeeping data logs three frame outages**
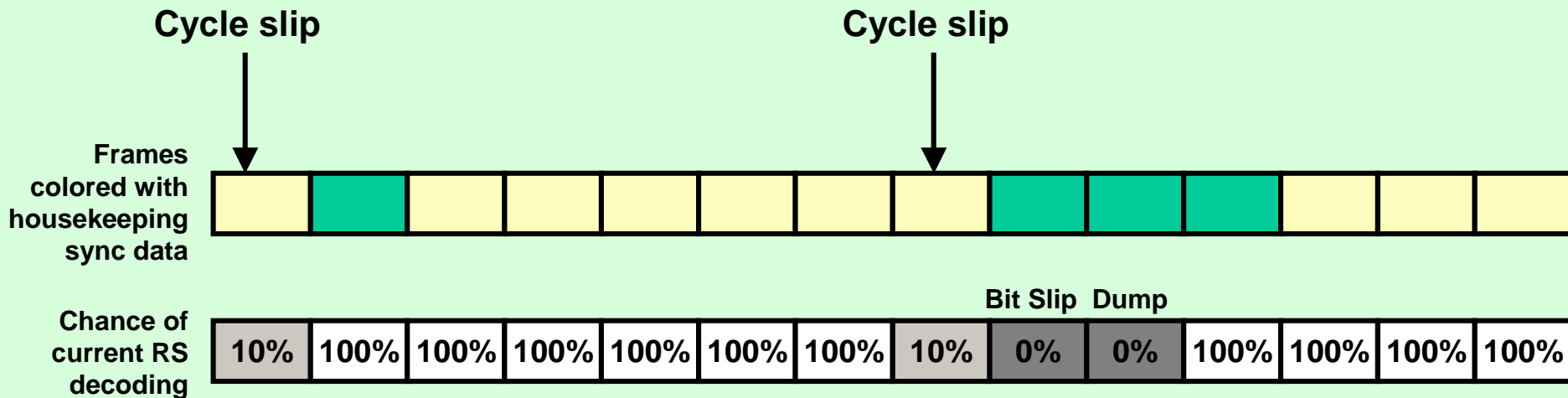- **This fully explains the 1-3 pattern and the correlation between frame and node sync**

HUYGENS RECOVERY TASK FORCE
HRTF Results
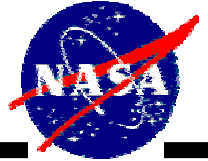## What Actually Happens to the Frames?

esa
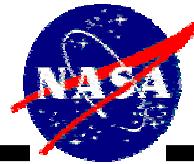
- **This corruption model helps us predict which frames will be returned to Earth and which of those will be recoverable**

- **Consider the following example**

Cycle slip　　　　　　　　　　　　　　**Cycle slip**

Frames colored with housekeeping sync data

Bit Slip Dump

Chance of current RS decoding

| 10%	100%	100%	100%	100%	100%	100%	10%	0%	0%	100%	100%	100%	100%

HRTF Results
This Explanation is Too Simple

- The 1-3 frame error sequence only occurs if the time between symbol slips is large enough

- Even in those cases, there are variations in the mechanism due to the fact that the symbols in the neighborhood of the slips are degraded by the DTTL

- Finally, the frame synchronizer is quite lenient and does not always notice out-of-sync frames immediately

- In reality, there are many distinct patterns of frame errors that are similar to this 1-3 pattern
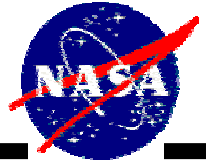
HRTF Results
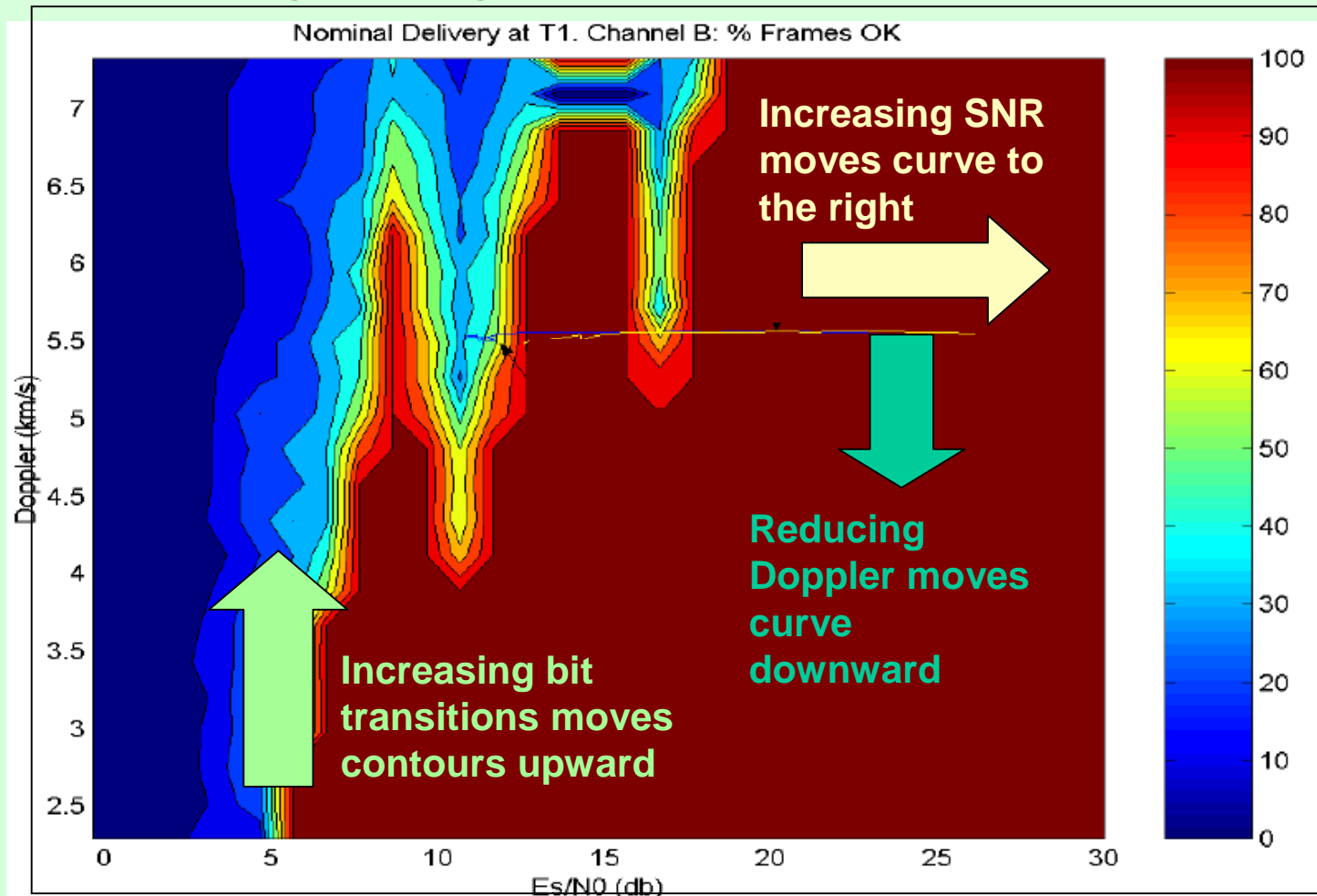## Simulation of the Mechanism
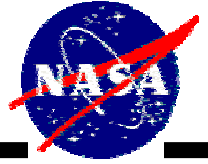
- **We created simulation software that mimics the effects of the frame synchronizer and Viterbi decoder**

- **The simulator takes, as input, DTTL phase offset as a function of time**

- **It produces, as output, a sequence of events that correspond to the status of frames**

  - **Good frames**

  - **Dropped frames: lost forever**

  - **Bit-slipped frames: can be easily corrected with a modified ground decoder**

  - **Corrupted frames**

- **This sequence of frame indicators were used by the probe science teams to evaluate various mission scenarios**
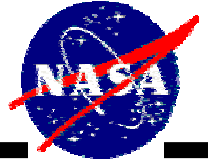
HRTF Results
Ways to Improve Data Return

Varying the critical parameters "moves" the probe curve with respect to the contours - resulting in more good data returned to Earth

Nominal Delivery at T1. Channel B: % Frames OK

Increasing SNR moves curve to the right

Reducing Doppler moves curve downward

**Increasing bit transitions moves contours upward**

HRTF Results
Bit Transition Probabilities

- **Since bit transition probability can affect the DTTL performance, we examined typical data streams from each probe instrument**

- **All instruments generate streams with close to 50% bit transition probability**

  - **Data appears nearly random**

  - **Instrument teams have done a good job in preprocessing their data**

- **We examined the possibility of applying precoding to increase the transition probability in the data stream**

  - **This is possible, but costs signal bandwidth (i.e. the amount of science data would have to be reduced)**

HRTF Results
Zero Packets
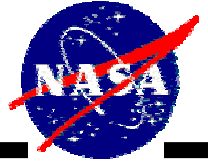
- **We also examined the possibility of periodically inserting packets consisting of all zeros**

  - **Since strings of zeros are converted (under coding) to alternating 0s and 1s, this has the effect of increasing the average bit transition probability of the data stream**

- **This also works well, but also reduces the available bandwidth of science data**

- **It is easier to do this than precode the science data**

- **If such an improvement is necessary, it will likely be implemented this way**
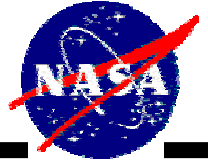
- **Once the data are on the ground, processing can be intensive and lengthy**

- **Frames can be examined to see if they are bit-slipped**

  - **Decoding of these frames will be easy**

- **Some corrupted frames can be recovered**

  - **If the corruption occurs close enough to the end of the frame, standard Reed-Solomon decoding can recover the frame**

  - **If the corruption occurs a bit earlier, it may still be possible to use the code's erasure correction capability to recover some frames**

  - **By using the fact that the frames have a very well-known structure, perhaps more frames can be decoded**

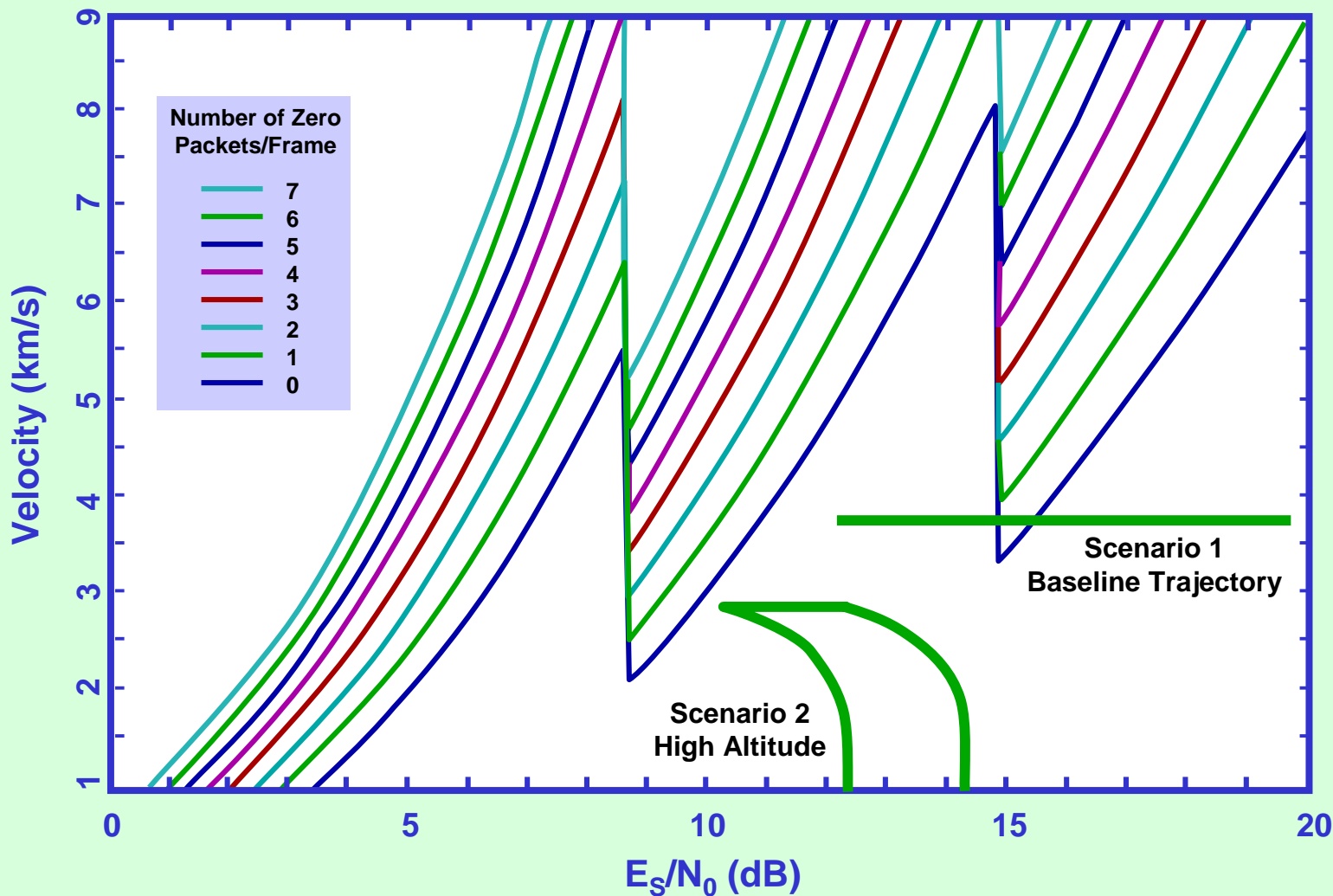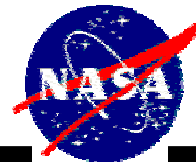 - **Stack decoding may be possible to recover still more frames**

HRTF Results
Status as of April, 2001
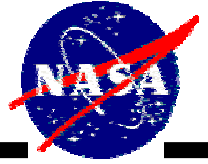
- **Based on all the analyses of the HRTF, two scenarios emerged as strong possible solutions**
- **Scenario 1**
  - **Keep the probe trajectory as is (baseline)**
  - **Decrease the Orbiter Delay Time (ODT) to avoid the initial "bad finger"**
  - **Modify ground decoders to recover more data**
  - **Preheat probe clock**
  - **Result: > 95% data return**
- **Scenario 2**
  - **Fly by at 50,000 km rather than the baseline 1,200 km, requires using ~150 m/s of propellant**
  - **Preheat probe clock**
  - **Adjust ODT for best performance**
  - **Result: 100% data return**
- **Science teams began assessing impact of the scenarios**
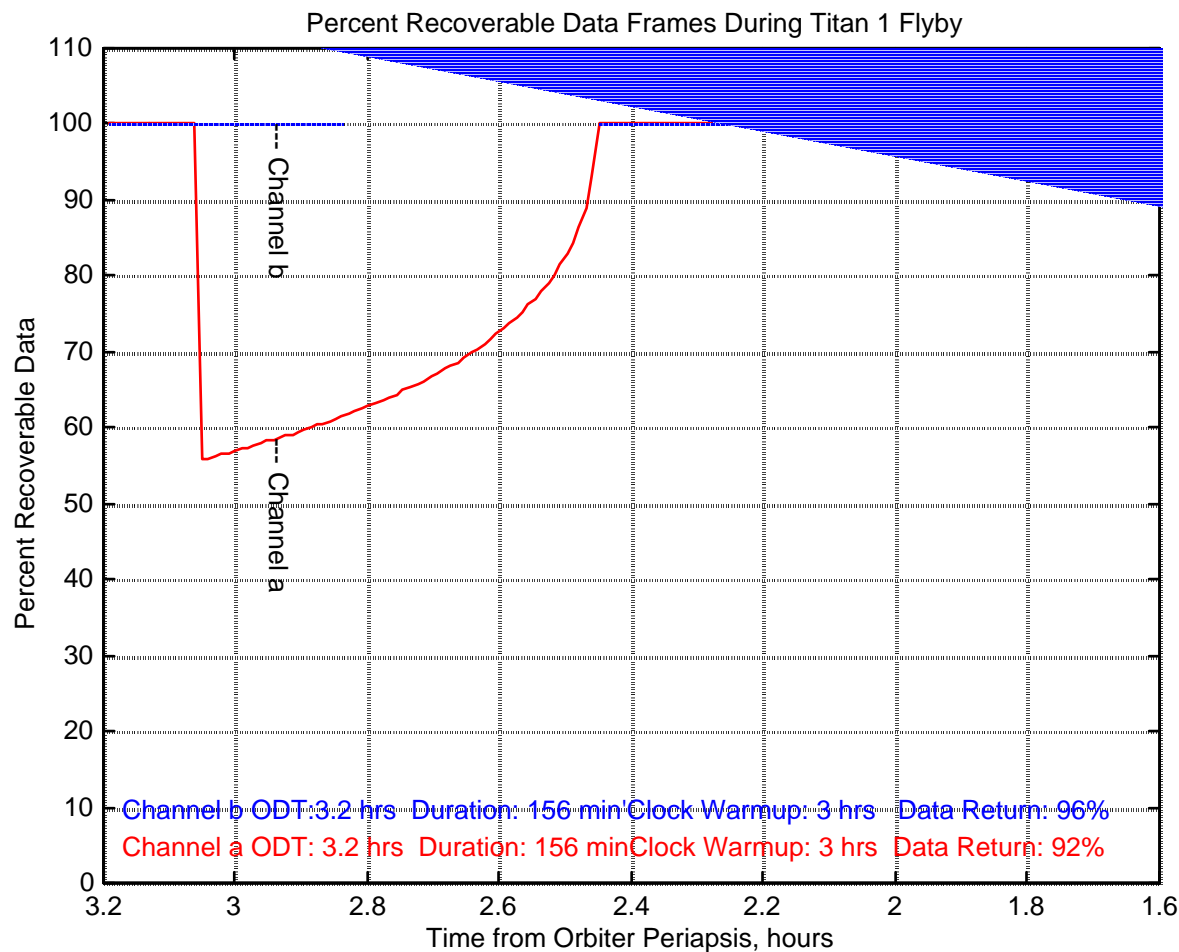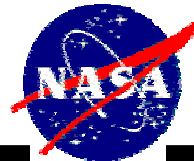 - **Used JPL simulation of error mechanism**

HRTF Results
The Two Scenarios

Number of Zero Packets/Frame

- 7
- 6
- 5
- 4
- 3
- 2
- 1
- 0

Y-axis: **Velocity (km/s)**

X-axis: **E_S/N_0 (dB)**

Scenario 1
Baseline Trajectory

Scenario 2
High Altitude

Percent Recoverable Data Frames During Titan 1 Flyby

- **Scenario 1 performance is given by this graph**

- **Scenario 2 is essentially lossless**

Channel b ODT: 3.2 hrs Duration: 156 min Clock Warmup: 3 hrs Data Return: 96%
Channel a ODT: 3.2 hrs Duration: 156 min Clock Warmup: 3 hrs Data Return: 92%
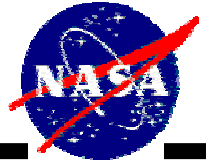
HRTF Results
## An HRTF Slip-Up: Oscillator Drift
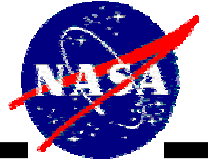
- The Huygens clock has been monitored carefully since launch

- The HRTF initial analysis of the clock showed a drift in our favor and a good absolute frequency as well

- With this understanding, the baseline Huygens trajectory would have worked

- Unfortunately, this analysis assumed the Cassini clock was known exactly

- In fact, the Cassini clock is off slightly from its design point

- This means we cannot live with the baseline trajectory
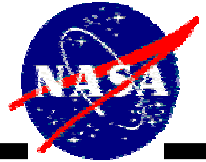
HRTF Results
The Unfortunate Truth!

- **Our new understanding of the clocks caused upward shifts of the solutions**
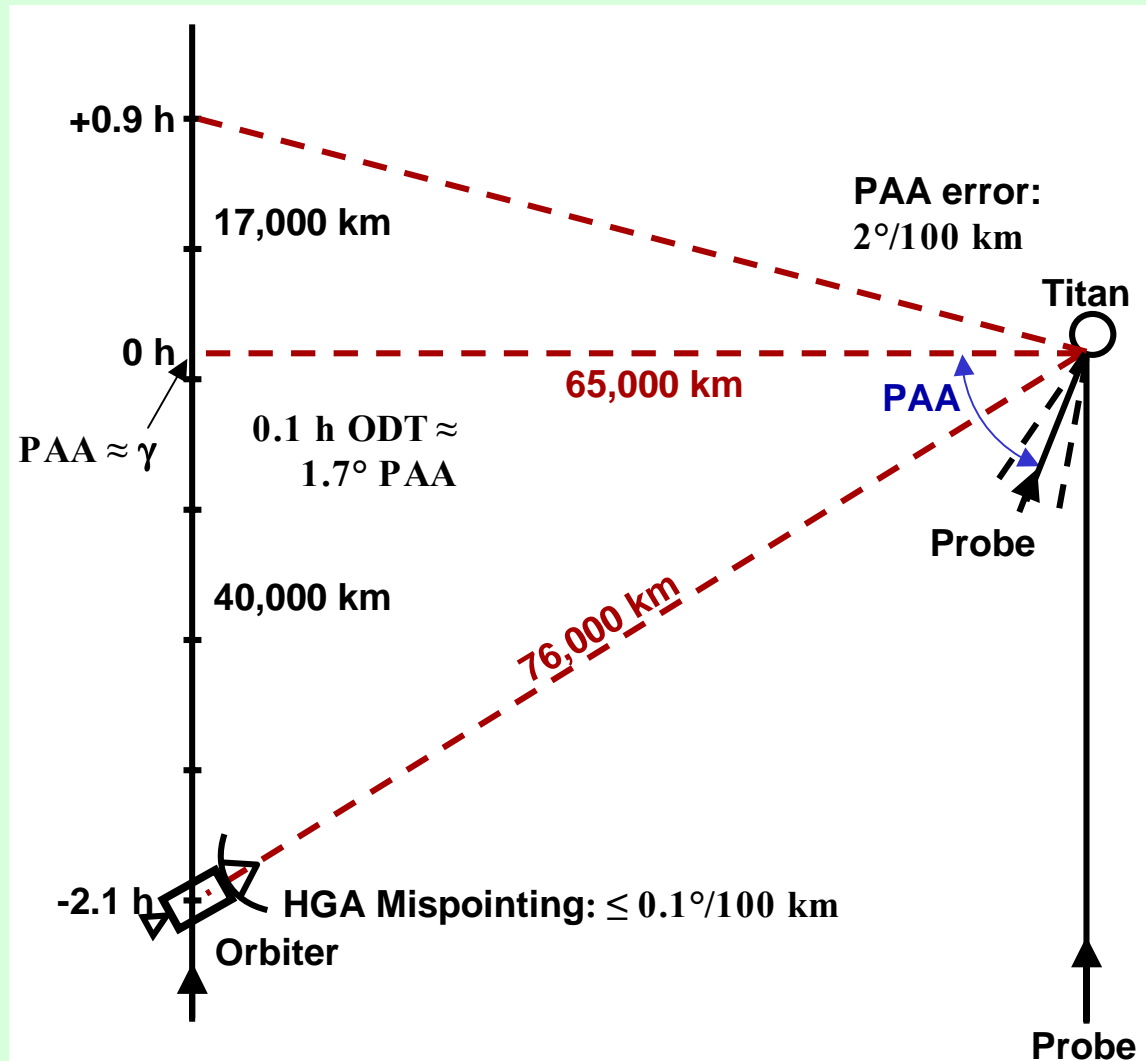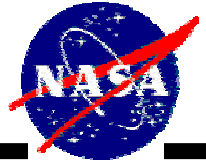- **Scenario 1 (baseline trajectory) is no longer viable**
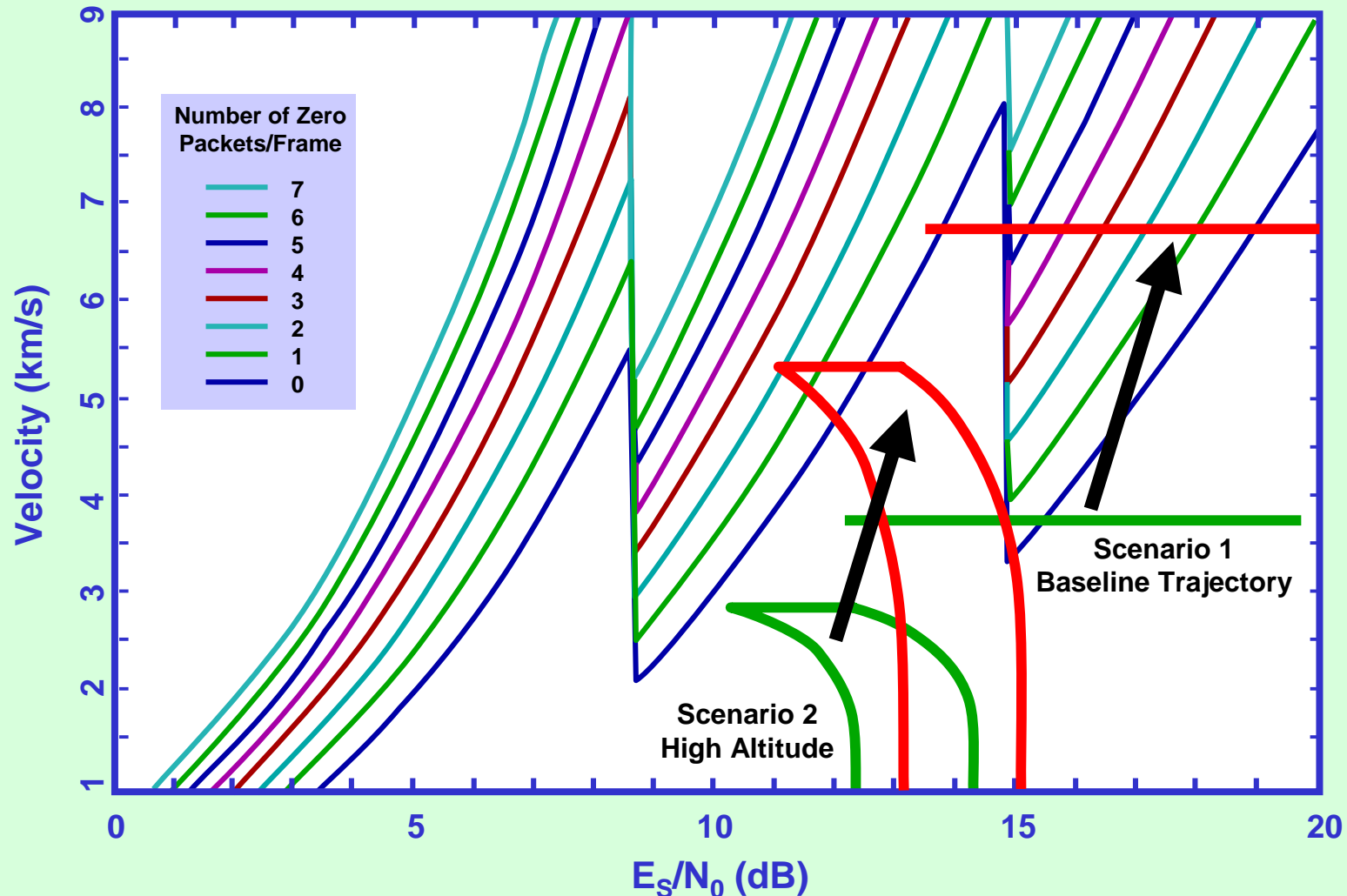
- **The trick now was to find a high altitude flyby that uses a lot less fuel than the old Scenario 2 (~150 m/s)**

- **JPL navigators came up with the idea of flying by the opposite side (retrograde) of Titan**

- This uses Titan's gravity to help more with Cassini maneuvers

- **New Scenario 2 can use as little as 80 m/s of propellant**

+0.9 h

17,000 km
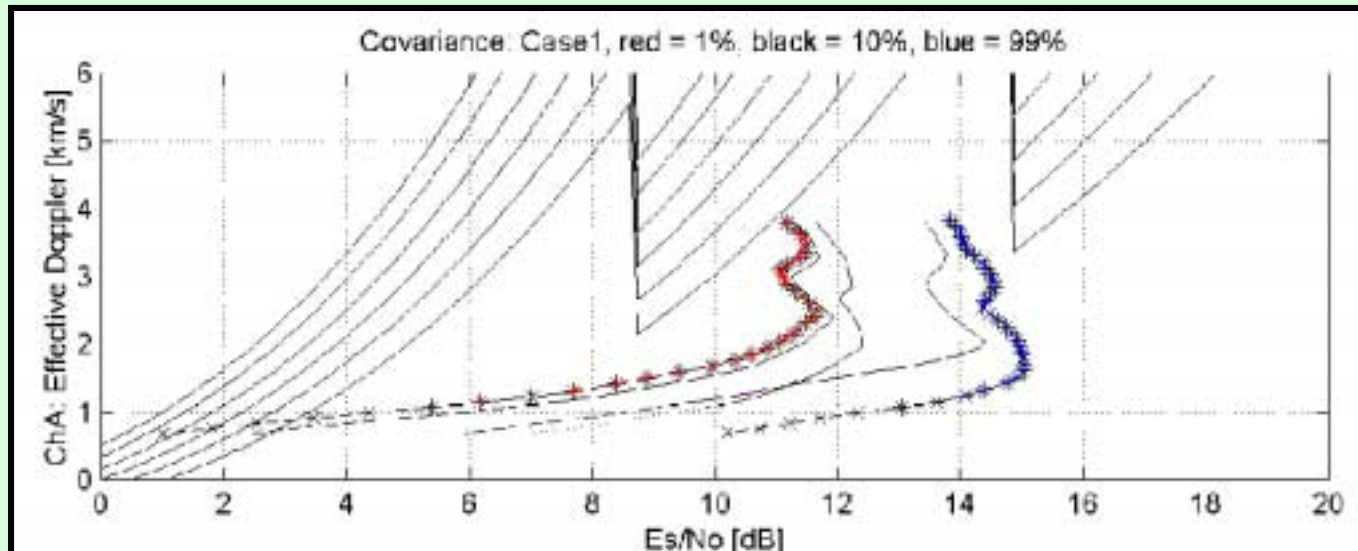
0 h

$PAA \approx \gamma$

0.1 h ODT $\approx$ 1.7° PAA

65,000 km

PAA error: 2°/100 km

Titan

PAA

Probe

40,000 km

76,000 km

-2.1 h

HGA Mispointing: $\leq 0.1°/100$ km
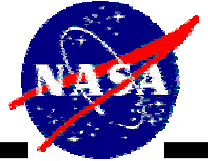
Orbiter

Probe

- **The HRTF developed several point designs that show possible solutions to the anomaly**

  - **Each of these returns close to 100% of the data with margin**

- **Here is an example design, Case 1:**

  - $SZA \approx 30°$

  - **Latitude of nominal landing point: -9° (South!)**

  - **99% link up to 156 minutes after entry**

  - **90% link up to 180 minutes after entry**

  - $PAA \leq 82°$

Covariance: Case1, red = 1%, black = 10%, blue = 99%

ChA: Effective Doppler [km/s] vs Es/No [dB]

HRTF Results
Conclusions

- **Solutions exist for the Huygens radio relay anomaly**

- **The solutions require using propellant**

- **The solution space must be searched by the implementation project to minimize propellant use**

  - **Leave as much propellant for other unforeseen problems as possible**

  - **Keep high probability of extended Cassini mission**

- **Learn from the mistakes that caused this problem (an problems in solving the problem!)**

  - **Test to all requirements before launch**

  - **Archive test results carefully**

  - **Never throw away data in a deep space communications link**

  - **Use appropriate amount of reconfigurability on spacecraft systems**